

EFFECTS OF SURROUNDING MEDIUM ON THE
PERFORMANCE OF EXPLODING ALUMINUM FOIL FUSES

T. L. Berger

Naval Surface Weapons Center
Dahlgren, Virginia 22448

Abstract

Flat aluminum foil fuses were exploded electrically by discharging a capacitor bank into a series combination inductance (~ 600 nH) and fuse. The $2.54 \times 2.54 \times 0.0023$ cm foils were exploded in a sealed chamber. The time to burst and fuse voltage characteristics were investigated as a function of the fuse environment. Results are given for foils exploded in various gases and liquids.

Introduction

Electrically exploded conductors are useful in a wide variety of pulsed power applications. Fast foil current breakers have been used to sharpen current pulses from capacitor banks¹⁻³ and from explosive magnetic flux compression generator-transformer systems⁴⁻⁷. In addition, fuses have been used as the high speed elements for multiple stage switching in inductive energy storage⁸⁻⁹. Exploding conductors have also been used to launch hypervelocity projectiles¹⁰⁻¹².

Despite a wide variety of experimental work, there remains much that is not understood about the electrical explosion of conductors. Edge effects which lead to breakdown, for example, are not well understood. It seems reasonable that breakdown at the edges of the foil is due to corona discharge and explosions due to irregularities which are introduced when the foil is cut. There is some

evidence, however, that there may be mechanisms other than corona discharge which lead to edge breakdown¹³. The effect of volume changes is also not well understood. Although electrical conductivity is known to be relatively sensitive to volume changes, a constant volume approximation is generally used in order to avoid difficult hydrodynamic calculations¹⁴. Finally, we mention the effects of the surrounding medium on fuse characteristics. It is not clear, for example, what the characteristics of the surrounding medium should be in order to best inhibit electrical breakdown. On the one hand, it is suggested that the surrounding medium should confine the metal vapor in order to inhibit collisionally induced ionization and subsequent breakdown¹. On the other hand, it has been suggested that heat transfer and chemical reactions with the surrounding medium can inhibit electrical breakdown¹⁵.

The purpose of this work is to attempt to gain a better understanding of the effects of the fuse environment on fuse performance. In this paper we report the results of measurements of the time to burst and peak hold off voltage for aluminum foils exploded in various gases and liquids.

Experimental Details

Flat aluminum foils $2.54 \times 2.54 \times 0.0023$ cm were exploded by discharging a capacitor bank into an inductance in series with the aluminum foil.

The capacitor bank is a low inductance bank with ignitron switches. The nominal charging voltage is 20 kV, the capacitance is 98 μ F, and the inductance is 80 nH. The maximum bank current is about 600 kA.

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The capacitor bank is coupled into a parallel plate transmission line by 15 coaxial cables. The total inductance of the system is 620 nH.

Fuse current was measured with a low inductance current viewing resistor. Fuse voltage was measured with a resistive divider.

Experimental Results and Discussion

Figure 1 is a typical example of current and voltage waveforms obtained in this work. Fig. 1 shows that there are a number of well defined stages in the discharge of the capacitor bank through the foil. For approximately the first 6 microseconds of the discharge, the fuse voltage changes very little. The foil resistance also changes very little and the current is not far from what is obtained in the case of zero resistance. At $t \approx 6$ microseconds, there is an abrupt change in the slope of the voltage curve. At this time, a solid to liquid phase transition is in progress. At $t \approx 8$ microseconds, there is a very sharp change in the slope of the voltage curve. At this time, a liquid to vapor phase transition is in progress and fuse resistance is rapidly increasing. After about 200 nanoseconds, however, the fuse resistance begins to decrease very rapidly presumably due to ionization and breakdown of the metallic vapor.

Figure 2 is a plot of the time to burst as a function of capacitor bank voltage for foils exploded in air. Time to burst is defined as the time to peak voltage measured from the point where the current departs from its initial value of zero. The solid line in Fig. 2 was plotted according to the theory of Masionnier et al.¹. According to this theory, the Joule heat power is equal to the rate of change of the internal energy of the foil. This leads to the equation

$$\frac{\sqrt{2} \omega C_1^2 V_o^2}{\pi S^2} \left(-\frac{1}{4} \sin 2\omega t + \frac{\omega t}{2} \right) = k_1 a, \quad (1)$$

where

$$a = \frac{\sqrt{2}}{\pi} \gamma \int_{T_o}^{T_v} \rho^{-1} de,$$

and

C_1 = bank capacitance

V_o = initial bank voltage

S = cross sectional area of the foil

ω = angular frequency of sinusoidal current

γ = mass density of foil

ρ = resistivity of foil

e = internal energy per unit mass

T_o = initial foil temperature

T_v = foil temperature at vaporization

The quantity a can be calculated from handbook tables and has the value $a = 2.2 \times 10^{16}$ for aluminum¹. This value of a corresponds to slow adiabatic heating at atmospheric pressure. The numerical factor k_1 takes into account the rapid heating encountered in exploding foils. Masionnier et al.¹ suggest

$$1 < k_1 < 3.$$

Using the measured value of ω and other known values of physical parameters, Eq. (1) was solved numerically. The solid line shown in Fig. 2 was obtained with $k_1 = 2.2$. The fit is seen to be quite good.

Time to burst as a function of capacitor bank voltage was also measured for foils exploded in distilled water and in aluminum oxide powder. Within the limits of experimental uncertainty, the results (not given in this paper) are the same as those obtained for foils exploded in air. We have also measured the time to burst for foils exploded in various gases and liquids. The results are given in Table I. These results show that the time to burst is not sensitive to changes in the surrounding medium. Since the thermal conductivity is much greater for water than air, it seems reasonable that more energy and hence more time would be required to obtain a given resistance change of the foil in water than in air. According to Burtsev et al.¹⁶, changing the relative resistance of the foil by a factor of 20 requires 4.5 kJ/g in water and 3.2 kJ/g in air. We have not observed this effect possibly because the natural frequency of our system is smaller by about a factor of 2. Our results, however, do agree with those of Salge et al.⁹.

We now consider the maximum standoff electric field measurements. These measurements were made for

foils exploded in various gases at pressures ranging from 0-200 psig and in various liquids over the density range 0.9 - 3.1 g/cm³. This was done in order to test the assumption of two models: the vaporization wave model¹⁷ and the heat transfer-chemical reaction model¹⁵.

According to the vaporization wave hypothesis, a vaporization wave propagates inward from the conductor surface. Ahead of the wave, the material remains in the conducting state while behind the wave, the material is in a vaporized insulating state. If the vapor cloud is free to expand, mean free path effects should eventually lead to ionization and breakdown in the vapor. This has been observed¹³. Breakdown should be inhibited by increasing the density of the surrounding medium.

Figure 3 is a plot of the maximum standoff electric field as a function of density for foils exploded in a 50% N₂ 50% O₂ gas mixture. This plot shows that the electric field does indeed increase with density in accordance with the vaporization wave theory. The same effect was observed for the other two gases used as shown in Table I. The peak electric field was very nearly the same in all the liquids except for transformer oil.

We now consider the heat transfer-chemical reaction model. Conte et al¹⁵ have used this model to explain their results for aluminum foils exploded in water. An exothermic chemical reaction between the foil and water is thought to occur. The extra heat drives the fuse toward higher resistance and more rapid explosion. Foils exploded in H₂O₂ exhibited higher holdoff voltage than foils exploded in H₂O presumably because H₂O₂ is more chemically active than H₂O.

In this investigation, we have searched for chemical reactions in gases and liquids. According to Table I, the maximum electric field for the gases tends to decrease with increasing oxygen concentration. The peak electric field was the same for H₂O as for the more chemically active H₂O₂. Thus, the results of this work provide no support for the chemical reaction model. We do not reject this model, however, because we have

not investigated other factors which may be important such as time to burst, foil dimensions, and rate of energy transfer.

It is interesting that at the same density, the peak electric field is greater for helium than for the other gases. This effect may be due to vapor cloud cooling since helium has a relatively high thermal conductivity.

Conclusions

In conclusion, this work indicates that time to burst is largely independent of the surrounding medium. We have also found no evidence that chemical reactions affect fuse performance. We have found some indication that heat transfer to the surrounding medium may inhibit breakdown. Finally, we have found that the hold off voltage increases with gas density in the pressure range 0-200 psi but there is a weak dependence on gas species.

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Table I. Experimental Summary

P = pressure

 ρ = density $\bar{\tau}$ = average value of time to burst \bar{E} = average value of maximum electric field

MI = methylene iodide

Medium	P psig	ρ mg/cm ³	$\bar{\tau}$ μ sec	E kV/cm	No. Shots
50% O ₂ 50% N ₂	0	1.2	8.6	3.2	6
"	25	3.4	8.7	3.6	6
"	100	9.6	8.8	4.2	6
"	200	18.1	8.9	4.6	3
AIR	0	1.2	8.7	3.2	1
	100	9.6	8.7	4.4	2
	200	18.1	8.7	5.0	6
HE	200	2.4	8.6	4.0	4
	300	3.6	8.9	4.2	1
Transformer Oil	-	0.9x10 ³	8.7	4.4	2
Water	-	1.0x10 ³	8.6	5.1	2
30% H ₂ O ₂	-	1.1x10 ³	8.7	5.0	2
CCl ₄	-	1.6x10 ³	8.6	4.9	2
50% CCl ₄ 50% MI	-	2.3x10 ³	8.5	4.9	2
MI	-	3.1x10 ³	8.4	5.0	2

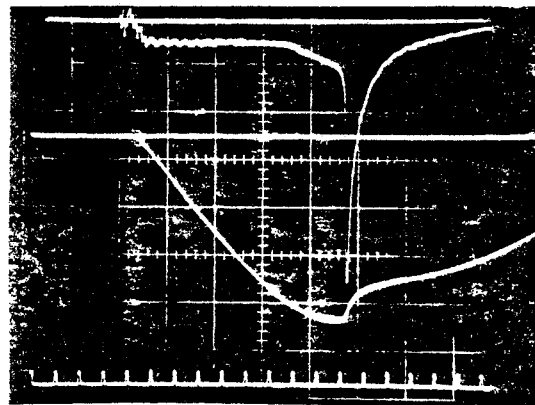


Figure 1. Current and voltage waveforms for foil exploded in 50% O₂ 50% N₂ at 200 psig. Upper trace: Fuse voltage; 2kV per division. Middle trace: Fuse current; 20kA per division. Lower Trace: one microsecond time marks.

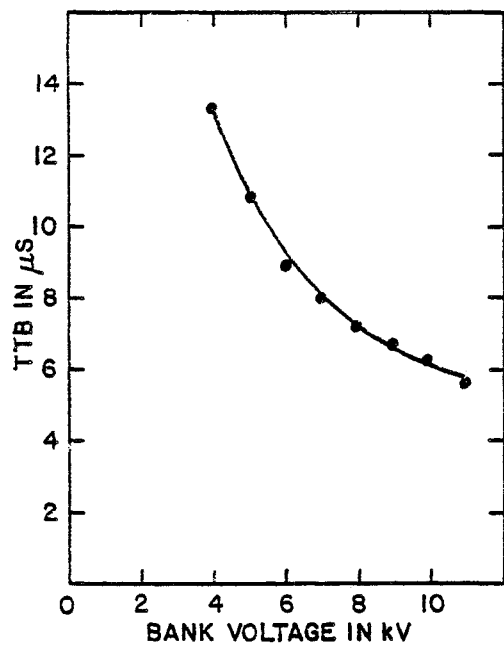


Figure 2. Time to burst (TTB) vs. bank voltage for foils exploded in air. Dots are experimental points and the curve is drawn according to the theory of Ref. 1.

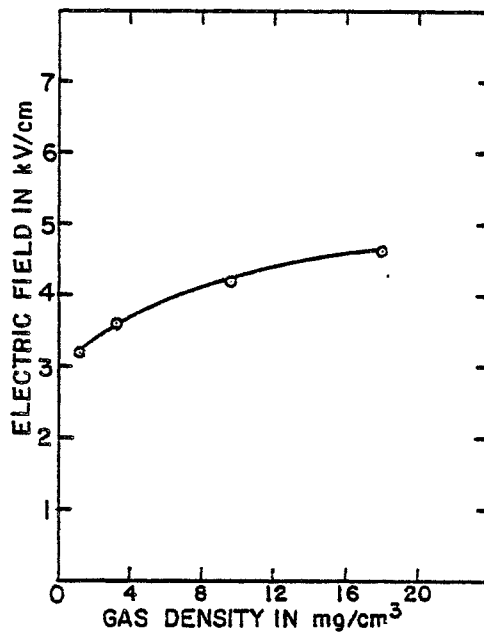


Figure 3. Peak electric field as a function of gas density for foils exploded in 50% O₂ 50% N₂.